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(54) **BROADBAND DUAL POLARIZED SLOTLINE FEED CIRCUIT**

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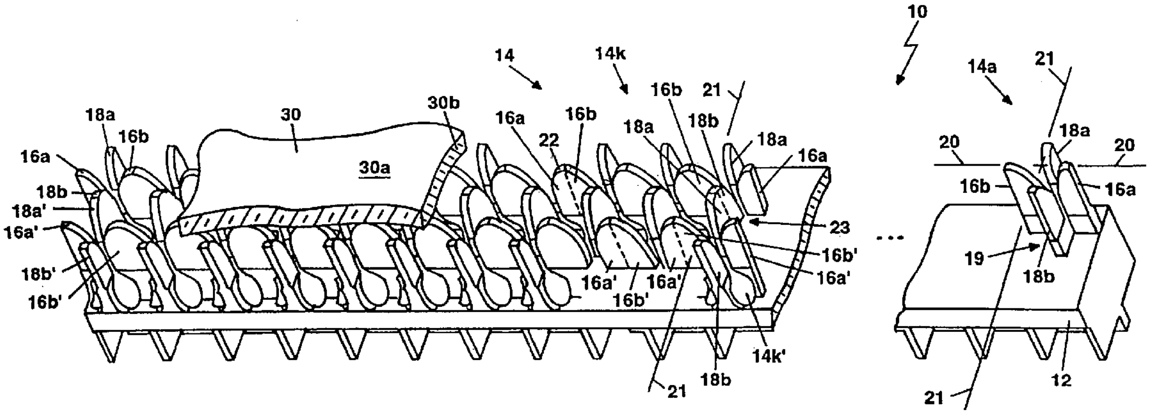
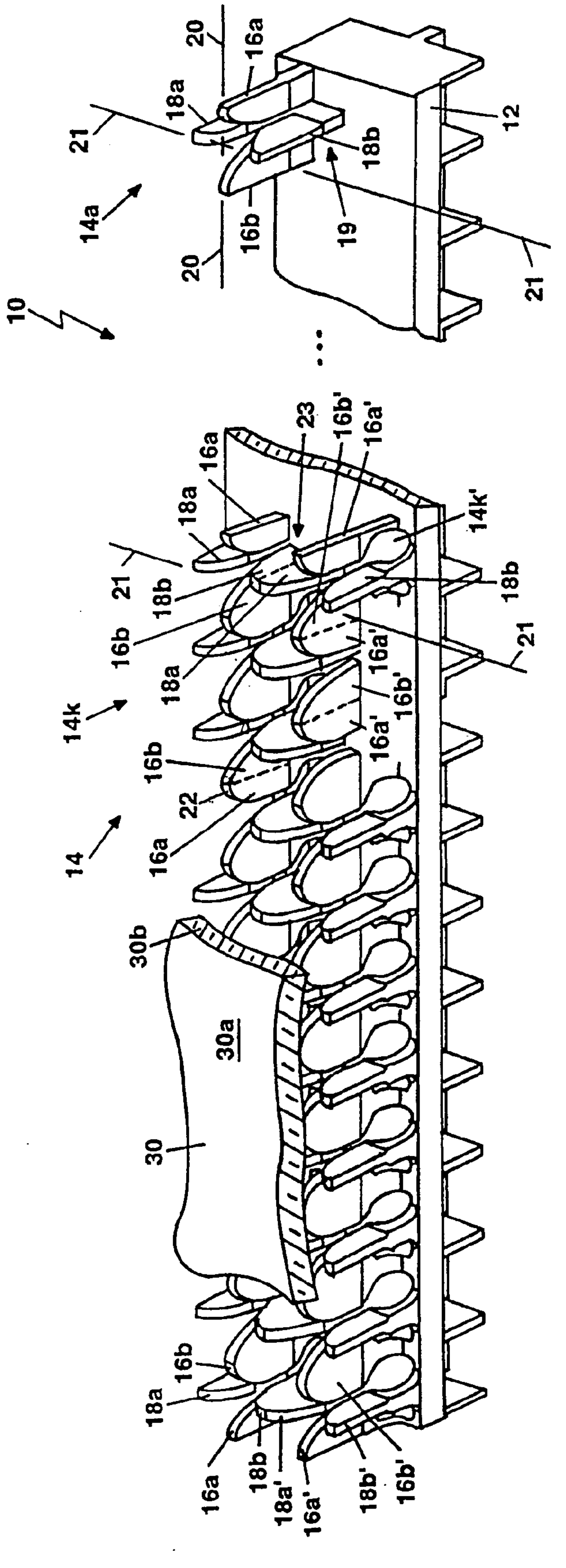
(57) **ABSTRACT**

A dual polarized slotline feed circuit includes a first slotline circuit and a second slotline circuit with the first and second slotline circuits disposed such that first slotline circuit is orthogonal to the second slotline and such that the first and second slotline circuits each have a first portion with a common centerline and wherein a second portion of one of the first and second slotline circuits is bent such that it is disposed at an angle with respect to the common centerline portion of the first and second slotline circuits.

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14a
20
16a
18a
21
18b
12
19
16b
20
21
14
14k
23
16b'
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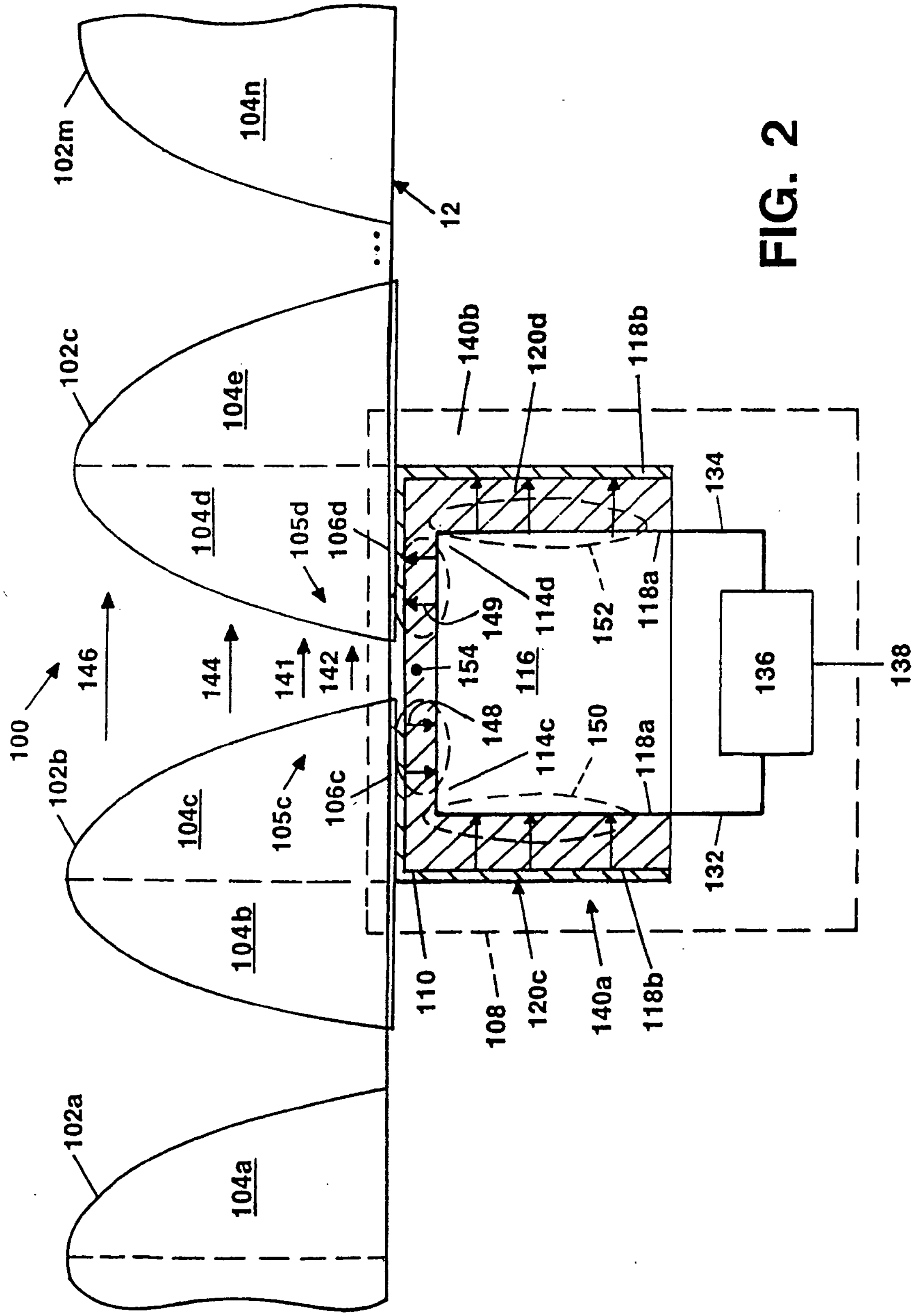
14k'
18b
21
18a
16b
18b
16a'
16b'
16a'
16b
22
16a
30b
30a
30
16b
18a
16a
18b
18a'
16a'
18b'
16b'

FIG. 1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12
102c
104e
104d
105d
106d
140b
120d
118b
134
114d
149
152
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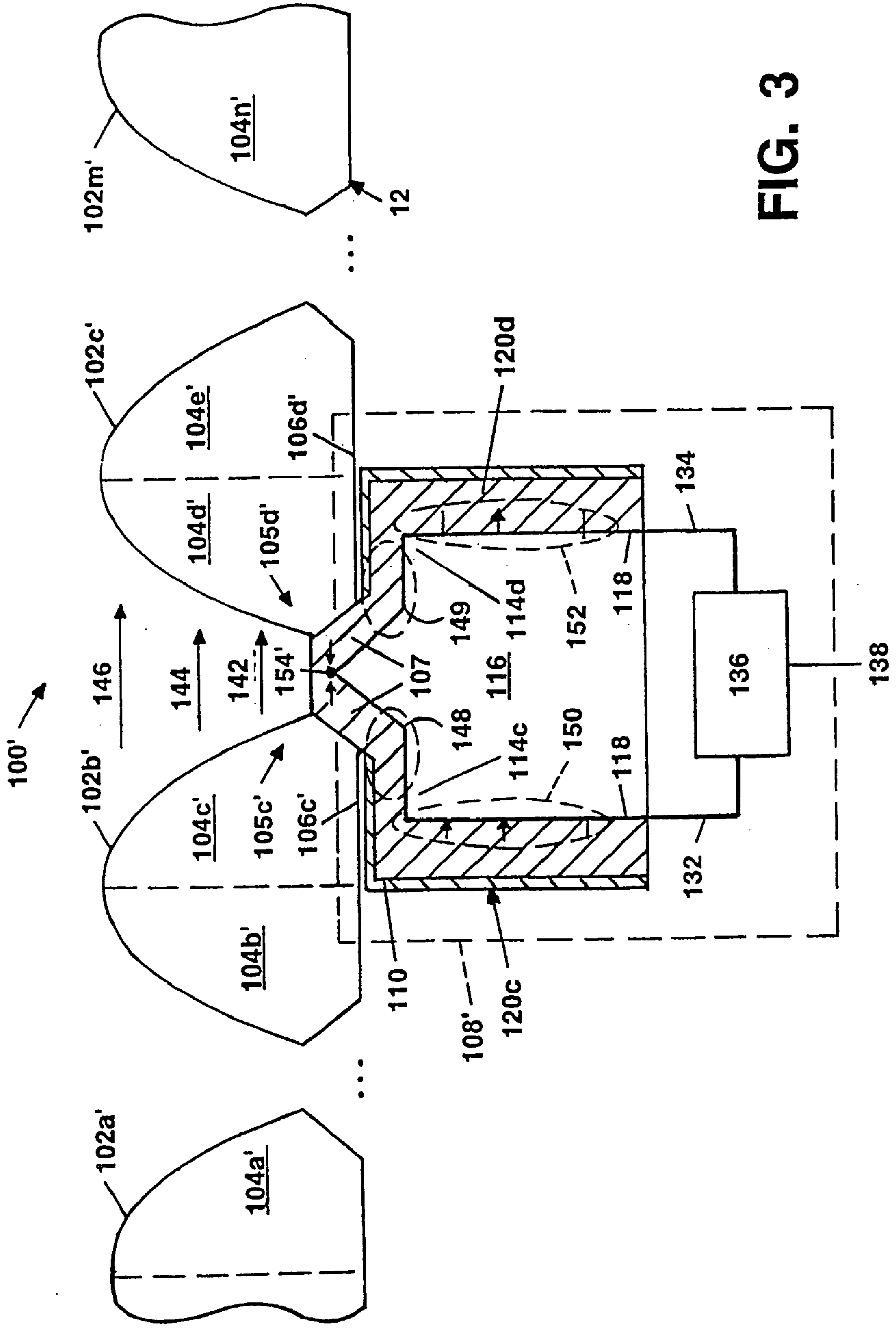
100
146
144
141
142
154
116
136
138
102b
104c
105c
106c
148
114c
150
118a
132
104b
110
108
120c
140a
118b
102a
104a

FIG. 2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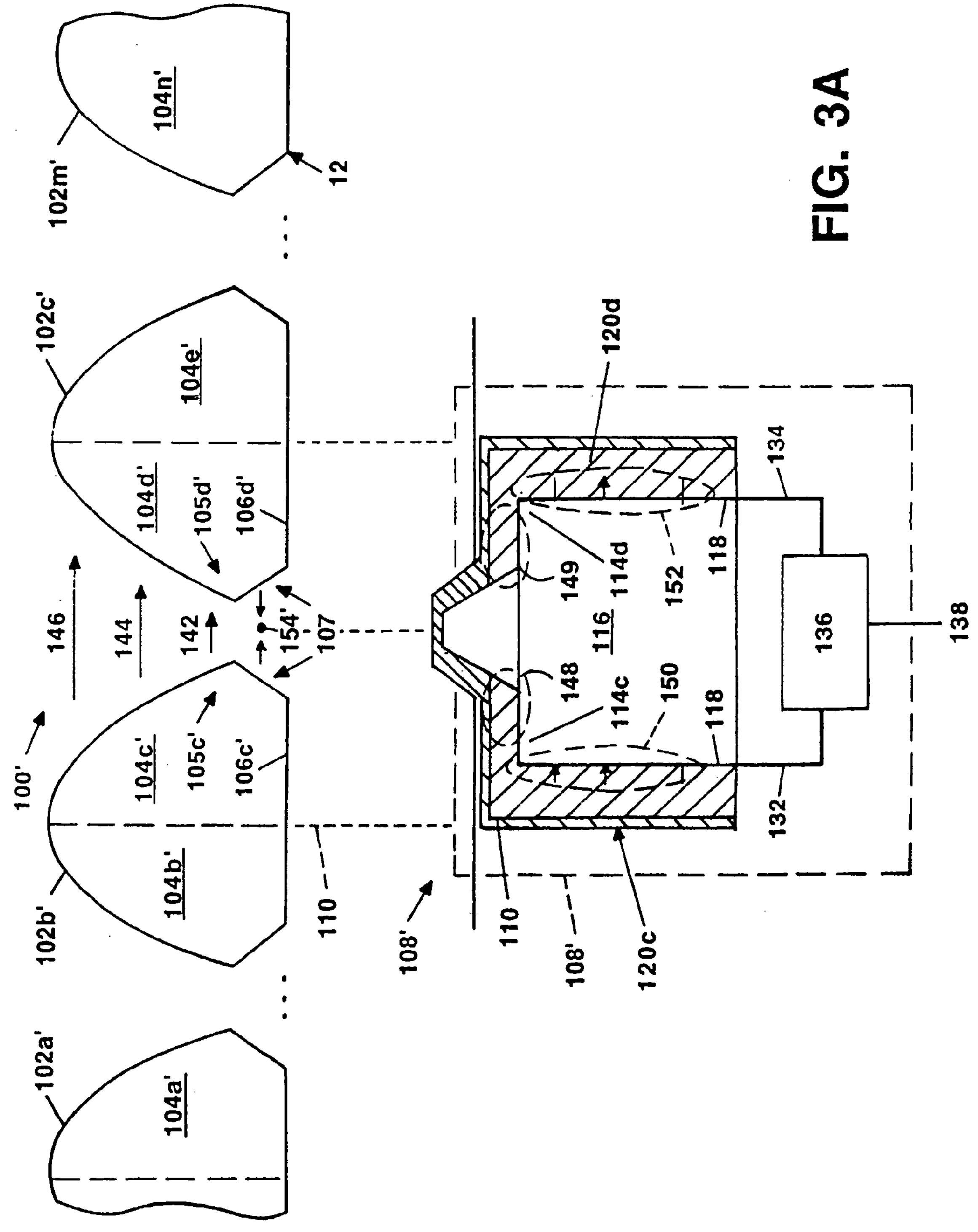
102a'
102b'
102c'
102m'
104a'
104b'
104c'
104d'
104e'
104n'
105c'
105d'
106c'
106d'
107
108'
110
114c
114d
116
118
118
120c
120d
132
134
136
138
142
144
146
148
149
150
152
154'
12

FIG. 3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104e'
104d'
105d'
106d'
102b'
104b'
104c'
105c'
106c'
102a'
104a'
100'
146
144
142
154'
107
110
108'
120c
120d
134
114d
149
116
152
118
148
114c
150
132
136
138

FIG. 3A

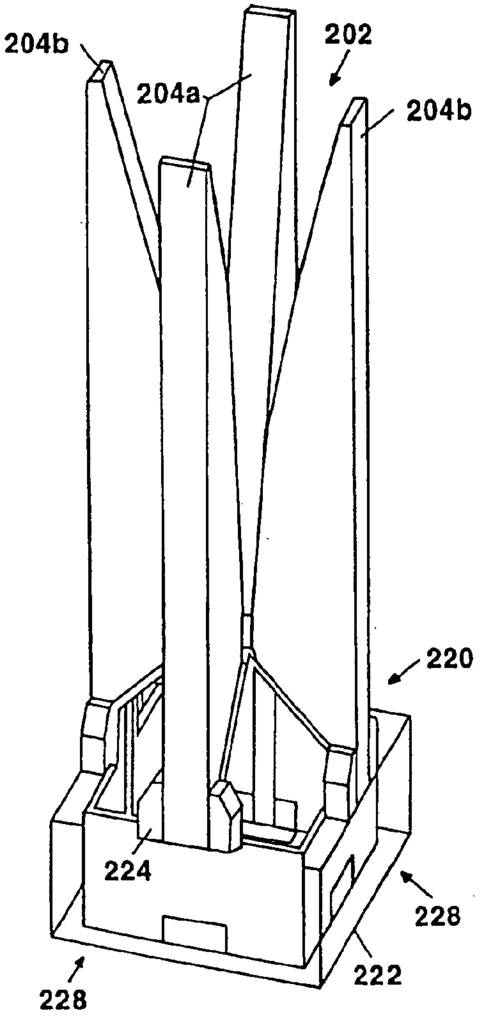
204b
204a
202
204b
220
224
228
222
228

FIG. 4

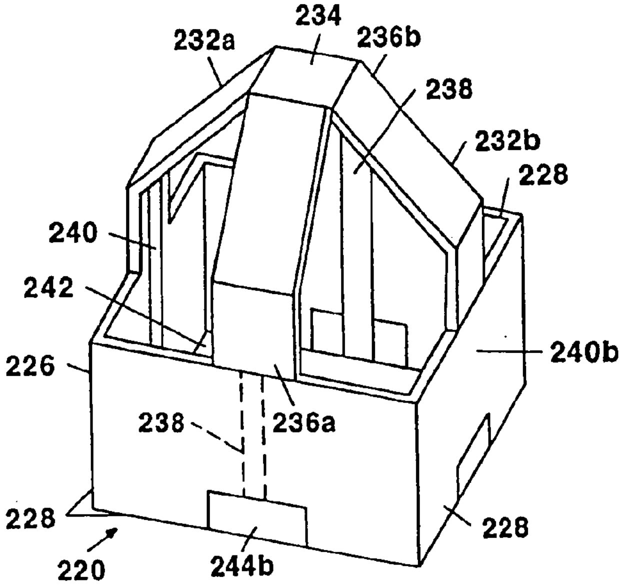
234
232a
236b
238
232b
228
240
242
240b
226
238
236a
228
220
244b
228

FIG. 4A

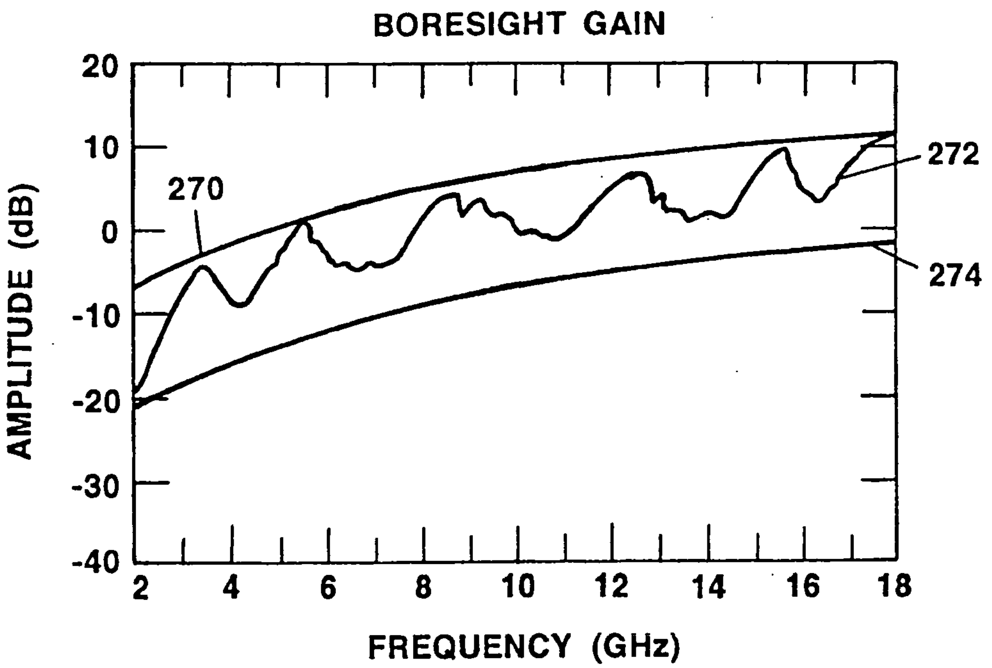

FIG. 5 (PRIOR ART)

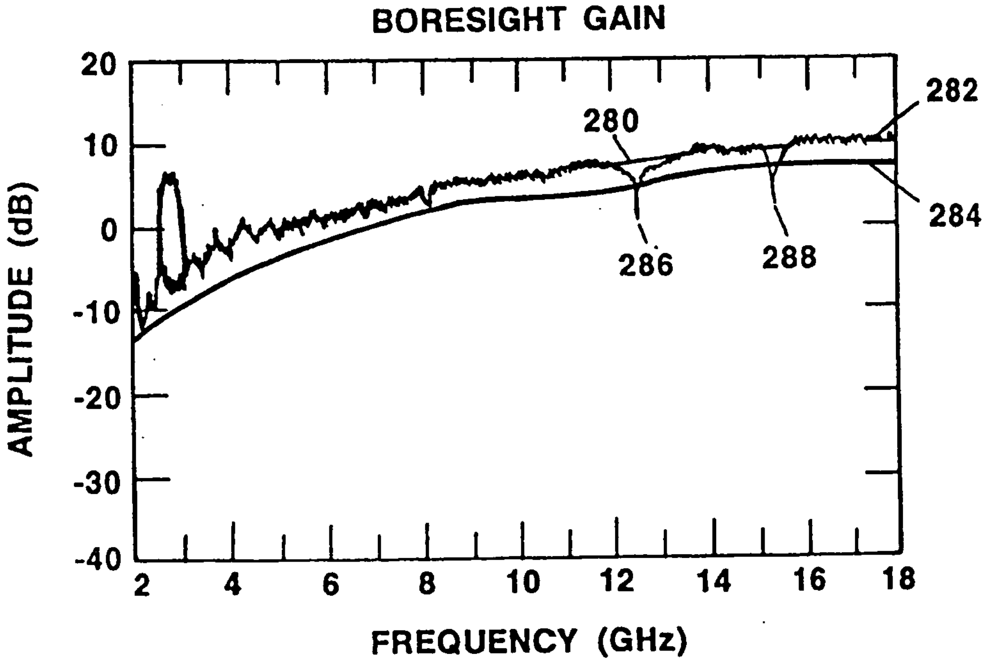

FIG. 5A

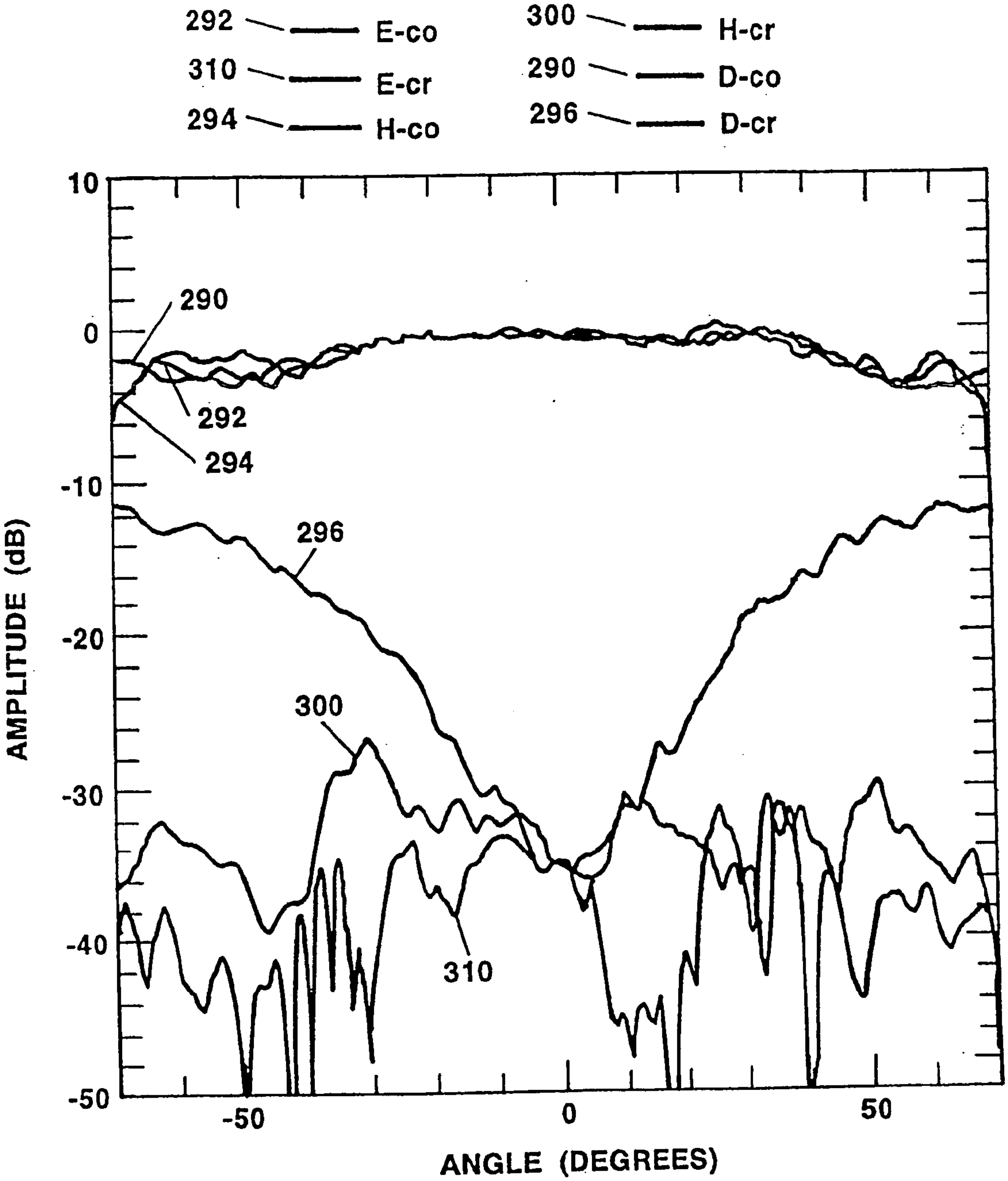
292 E-co
310 E-cr
294 H-co
300 H-cr
290 D-co
296 D-cr
10
0
-10
-20
-30
-40
-50
AMPLITUDE (dB)
290
292
294
296
300
310
-50
0
50
ANGLE (DEGREES)

FIG. 6

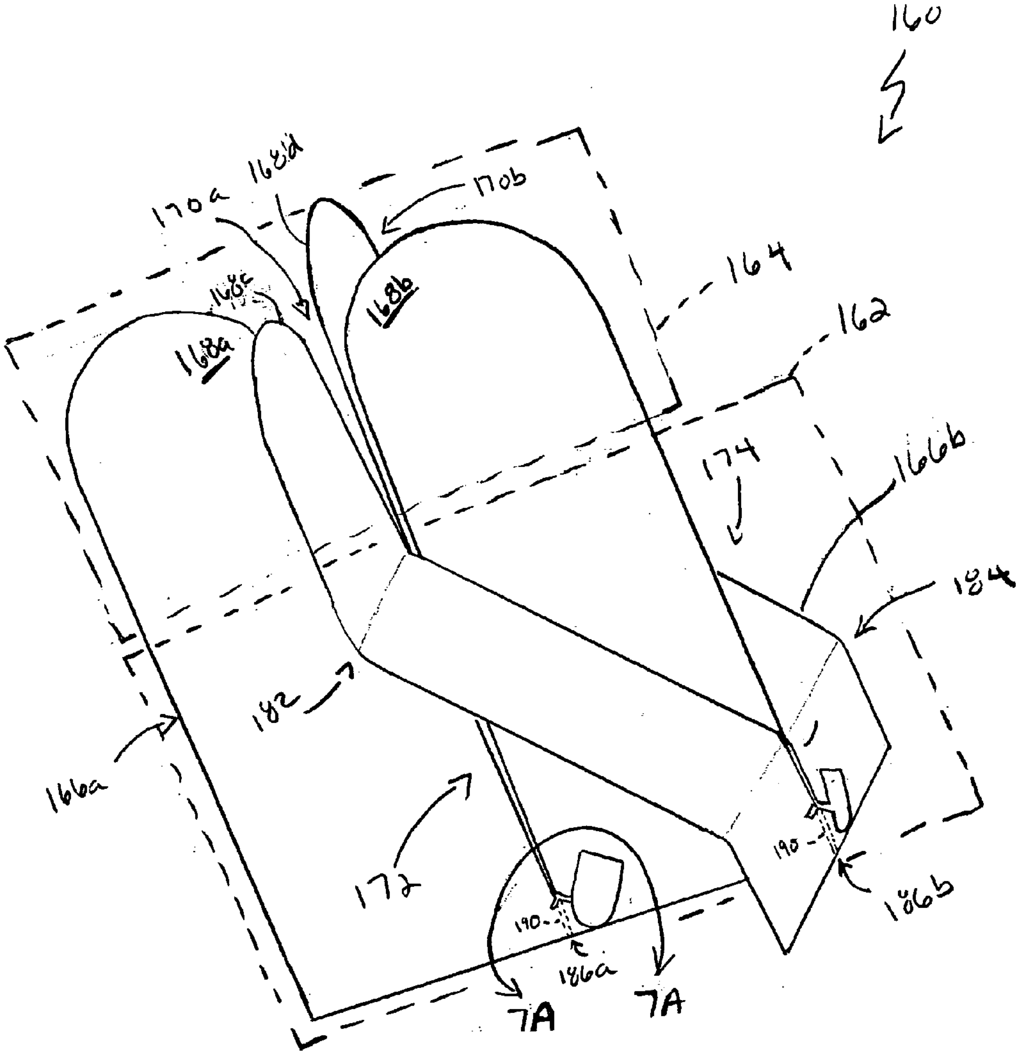
160
170a
168d
170b
164
168c
168b
168a
162
174
166b
184
182
166a
172
190
186b
190
186a
7A
7A

Fig 7

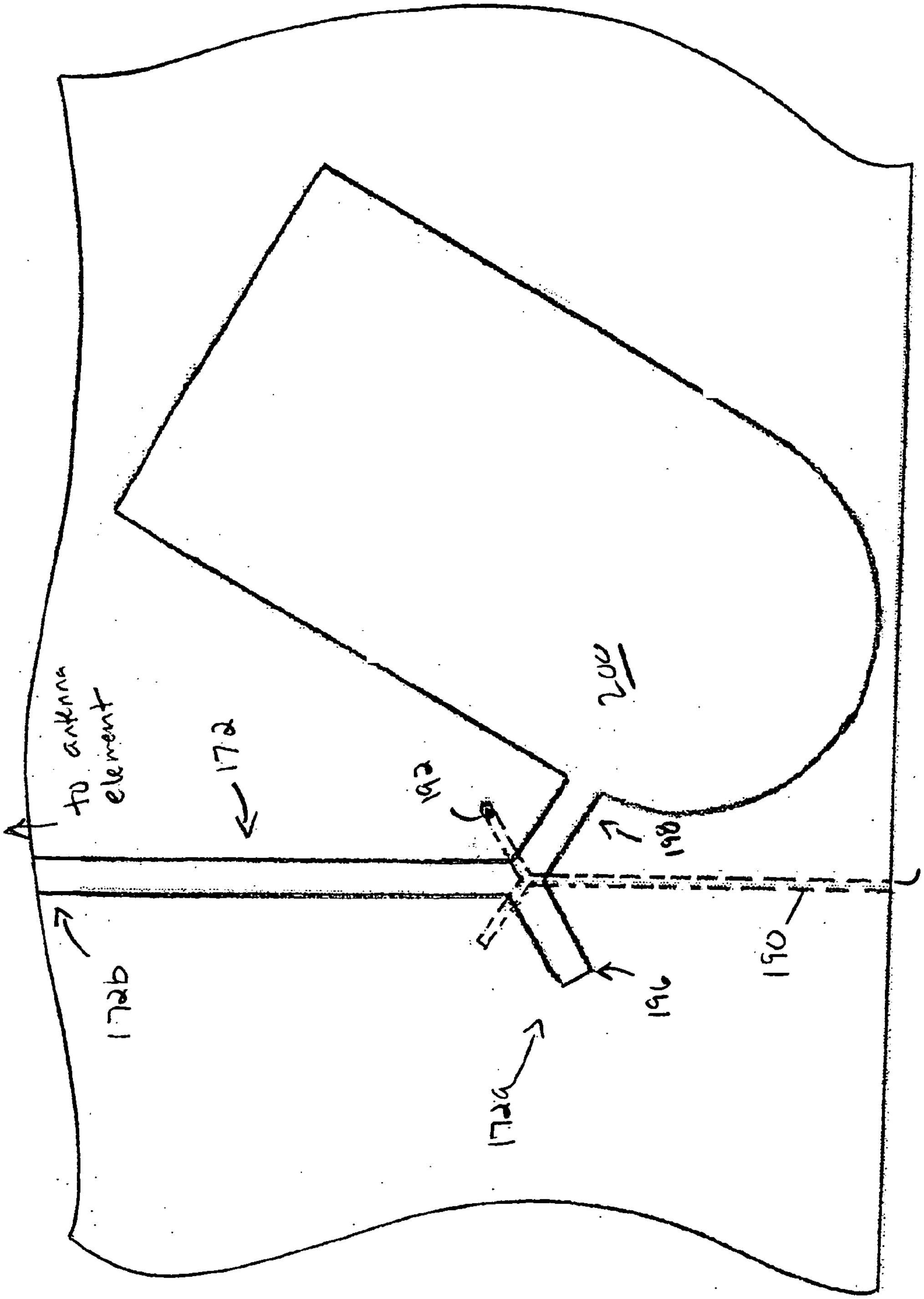

Fig. 7A

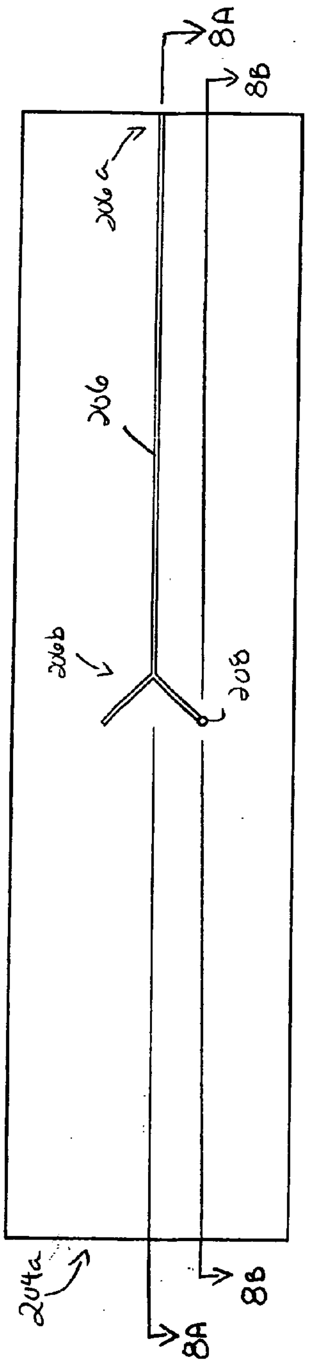

Fig 8

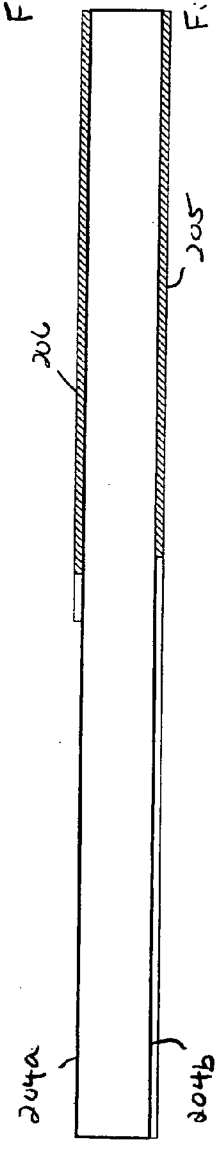

Fig 8A

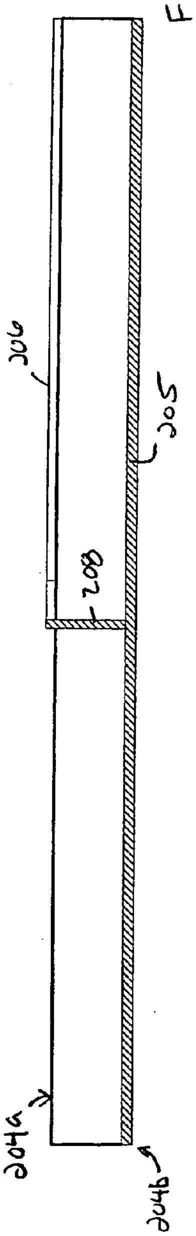

Fig 8B

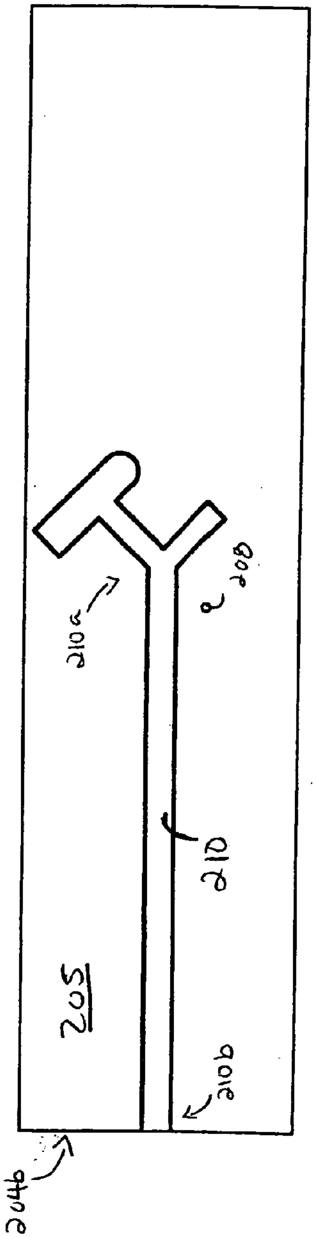

Fig 8C

BROADBAND DUAL POLARIZED SLOTLINE FEED CIRCUIT

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This application is a continuation-in-part (CIP) of co-pending application Ser. No. 10/617,620, filed Jul. 11, 2003 and this application claims the benefit under 35 U.S.C. s. 119(e) of U.S. Provisional application No. 60/518,813 filed Nov. 10, 2003, which is application is hereby incorporated herein by reference in its entirety.

STATEMENTS REGARDING FEDERALLY SPONSORED RESEARCH

[0002] This invention was made with government support under Contract No. N-00014-99-C-0314 awarded by the Department of the Navy. The government has certain rights in the invention.

FIELD OF THE INVENTION

[0003] This invention relates generally to radio frequency (RF) circuits and more particularly to RF feed circuits for notch radiator antenna elements.

BACKGROUND OF THE INVENTION

[0004] In communication systems, radar, direction finding and other broadband multifunction systems, having limited aperture space, it is often desirable to efficiently couple a radio frequency transmitter and receiver to an antenna having an array of broadband radiator elements.

[0005] Conventional known broadband phased array radiators generally suffer from significant polarization degradation at large scan angles in the diagonal scan planes. This limitation can force a polarization weighting network to heavily weight a single polarization. This weighting results in the transmit array having poor antenna radiation efficiency because the unweighted polarization signal must supply most of the antenna Effective Isotropic Radiated Power (EIRP) of the transmitted signal.

[0006] Conventional broadband phased array radiators generally use a simple, but asymmetrical feed or similar arrangement. Since a conventional broadband radiator is capable of supporting a relatively large set of higher-order propagation modes, the feed region acts as the launcher for these high-order propagation mode signals. The feed is essentially the mode selector or filter. When the feed incorporates asymmetry in the orientation of launched fields or the physical symmetry of the feed region, higher-order modes are excited. Those modes then propagate to the aperture. The higher-order modes cause problems in the radiator performance. Since higher-order modes propagate at differing phase velocities, the field at the aperture is the superposition of multiply excited modes. The result is sharp deviations from uniform magnitude and phase in the unit cell fields. The fundamental mode aperture excitation is relatively simple, usually resulting from the TE_{01} mode, with a cosine distribution in the E-plane and uniform field in the H-plane. Significant deviations from the fundamental mode result from the excited higher-order modes, and the higher order modes are responsible for the radiating element's resonance and scan blindness.

[0007] Another effect produced by the presence of higher-order mode propagation in the asymmetrically-fed wideband radiator is cross-polarization. Particularly in the diagonal planes, many higher-order modes include an asymmetry that excites the cross-polarized field. The cross-polarized field is in turn responsible for an unbalanced weighting in the antenna's polarization weighting network, which can be responsible for low array transmit power efficiency.

[0008] There is a need for broadband radiating elements used in phased array antennas for communications, radar and electronic warfare systems with reduced numbers of apertures required for multiple applications. In these applications, minimum bandwidths of 3:1 are required, but 10:1 bandwidths or greater are desired. The radiating element must be capable of transmitting and receiving vertical and/or horizontal linear polarization, right-hand and/or left-hand circular polarization or a combination of each depending on the application and the number of radiating beams required. It is desireable for the foot print of the radiator to be as small as possible and to fit within the unit cell of the array to reduce the radiator profile, weight and cost.

[0009] Prior attempts to provide broadband radiators have used bulky radiators and feed structures without co-located (coincident) radiation pattern phase centers. The conventional radiators also typically have relatively poor cross-polarization isolation characteristics in the diagonal planes.

[0010] In an attempt to solve these problems, a conventional quad-notch type radiator having a shape approximately one half the typical size of a full sized notch radiator ($0.2\lambda_L$ vs $0.4\lambda_L$, where λ_L is the wavelength for the low frequency) has been adapted to include four separate radiators within a unit cell. This arrangement allows for a virtual co-located phase center for each unit cell, but requires a relatively complicated feed structure.

[0011] The typical quad-notch radiator requires a separate feed/balun for each of the four radiators within the unit cell plus another set of feed networks to combine the pair of radiators used for each polarization. Previously fabricated notch radiators used microstrip or stripline circuits feeding a slotline for the RF signal input and output of the radiating element. Unfortunately these conventional types of feed structures allow multiple signal propagation modes to be generated within each unit cell area causing a reduction in the cross polarization isolation levels, especially in the diagonal planes.

SUMMARY OF THE INVENTION

[0012] In accordance with the present invention, a feed circuit includes a first slotline circuit and a second slotline circuit disposed such that it is orthogonal to the first slotline circuit and at least a portion of a centerline region of the first slotline circuit and at least a portion of a centerline region of the second slotline circuit are substantially aligned such that at least a portion of the first and second slotline circuits share a common centerline.

[0013] With this particular arrangement, a dual polarized slotline feed circuit is provided. By providing the feed circuit from two orthogonally disposed slotline feed circuits, the feed circuit can support dual polarizations over a frequency bandwidth which is relativley wide compared with the frequency bandwidth of other types of feed circuits.

Also, by providing the first and second feed circuits having common centerline portions, a slotline feed circuit having coincident phase-centers for each polarization is provided. This allows the feed circuit to efficiently feed antenna elements, such as cross-notch radiator elements, which are orthogonal to each other and which share a coincident phase-center. Also, by angling or bending a portion of one of the feed circuits with respect to the common centerline portion, feed circuit input lines can be physically separated from each other. This allows the slotline circuits to be fed independently of each other. In one embodiment, one of the slotline feed circuits includes both first and second bends which allows the input port of each of the slotline feed circuit to be placed in a desired located relative to the input port of the other slotline feed circuit. Also, by utilizing a bend in at least one of the first and second slotline feed circuits, a relatively simple dual polarized feed circuit is provided.

[0014] By providing the feed circuit from slotline feed circuits, the mechanical structure of the feed is such that it is relatively easily to attached the feed to double-Y baluns which are designed to utilize opposing boundary conditions in order operate over a wide bandwidth. Thus, in one embodiment, the slotline feed circuits each utilize a double Y balun.

[0015] In one embodiment, the slotline feed circuits are provided from printed circuit boards (PCBs) and a first one of the slotline feed circuit PCBs is provided with an opening (or slot) having a width selected to accept the width of a second one of the slotline feed circuit PCBs. Thus, the second slotline feed circuit PCB is inserted into the slot of the first slotline feed circuit PCB. The PCBS are arranged such that at least a portion of a centerline region of the first slotline circuit and at least a portion of a centerline region of the second slotline circuit are substantially aligned and at least a portion of the first and second slotline circuits share a common centerline. The first slotline feed circuit PCB is provided having at least one bend which physically separates the input ports of each of the slotline feed circuits. In some embodiments, the first slotline feed circuit PCB can be provided having two or more bends as needed to located the feed circuit input port in a desired location.

BRIEF DESCRIPTION OF THE DRAWINGS

[0016] The foregoing features of this invention, as well as the invention itself, may be more fully understood from the following description of the drawings in which:

[0017] **FIG. 1** is an isometric view of an array of notch radiators provided from a plurality of fin elements;

[0018] **FIG. 2** is a cross sectional view of a portion of a unit cell of an alternate embodiment of the radiator array of **FIG. 1** including a balanced symmetrical feed circuit;

[0019] **FIG. 3** is a cross sectional view of a portion of a unit cell of the radiator array of **FIG. 1** including a raised balanced symmetrical feed circuit;

[0020] **FIG. 3A** is an exploded cross sectional view of **FIG. 3** illustrating the coupling of a portion of a unit cell to the raised balanced symmetrical feed circuit;

[0021] **FIG. 4** is an isometric view of a unit cell;

[0022] **FIG. 4A** is an isometric view of the balanced symmetrical feed of **FIG. 4**;

[0023] **FIG. 5** is a frequency response curve of a prior art radiator array;

[0024] **FIG. 5A** is a frequency response curve of the radiator array of **FIG. 1**;

[0025] **FIG. 6** is a radiation pattern of field power for a single antenna element of the type shown in the array of **FIG. 1** embedded in the center of an array with all other radiators terminated. Patterns are given for the co-polarized and cross-polarized performance for the various planes (E, H, and diagonal (D)); and

[0026] **FIG. 7** is An isometric view of a unit cell having a dual polarized slotline feed circuit;

[0027] **FIG. 7A** is an enlarged view of the slotline feed circuit shown in **FIG. 7** taken along lines **7A-7A** in **FIG. 7**;

[0028] **FIG. 8** is a top view of a portion of a slotline feed circuit;

[0029] **FIG. 8A** is a cross-section side view of the portion of the slotline feed circuit of **FIG. 8** taken along lines **8A-8A** in **FIG. 8**;

[0030] **FIG. 8B** is a cross-section side view of the portion of the slotline feed circuit of **FIG. 8** taken along lines **8B-8B** in **FIG. 8**; and

[0031] **FIG. 8C** is a bottom view of the portion of the slotline feed circuit shown in **FIG. 8**.

DETAILED DESCRIPTION OF THE INVENTION

[0032] Before describing the antenna system of the present invention, it should be noted that reference is sometimes made herein to an array antenna having a particular array shape (e.g. a planar array). One of ordinary skill in the art will appreciate of course that the techniques described herein are applicable to various sizes and shapes of array antennas. It should thus be noted that although the description provided herein below describes the inventive concepts in the context of a rectangular array antenna, those of ordinary skill in the art will appreciate that the concepts equally apply to other sizes and shapes of array antennas including, but not limited to, arbitrary shaped planar array antennas as well as cylindrical, conical, spherical and arbitrary shaped conformal array antennas.

[0033] Reference is also sometimes made herein to the array antenna including a radiating element of a particular size and shape. For example, one type of radiating element is a so-called notch element having a tapered shape and a size compatible with operation over a particular frequency range (e.g. 2-18 GHz). Those of ordinary skill in the art will recognize, of course that other shapes of antenna elements may also be used and that the size of one or more radiating elements may be selected for operation over any frequency range in the RF frequency range (e.g. any frequency in the range from below 1 GHz to above 50 GHz).

[0034] Also, reference is sometimes made herein to generation of an antenna beam having a particular shape or beamwidth. Those of ordinary skill in the art will appreciate, of course, that antenna beams having other shapes and widths may also be used and may be provided using known techniques such as by inclusion of amplitude and phase adjustment circuits into appropriate locations in an antenna feed circuit.

[**0035**] Referring now to **FIG. 1**, an exemplary wideband antenna **10** according to the invention includes a cavity plate **12** and an array of notch antenna elements generally denoted **14**. Each of the notch antenna elements **14** is provided from a so-called "unit cell" disposed on the cavity plate **12**. Stated differently, each unit cell forms a notch antenna element **14**. It should be appreciated that, for clarity, only a portion of the antenna **10** corresponding to a two by sixteen linear array of notch antenna elements **14** (or unit cells **14**) is shown in **FIG. 1**.

[**0036**] Taking a unit cell **14***a* as representative of each of the unit cells **14**, unit cell **14***a* is provided from four fin-shaped members **16***a*, **16***b*, **18***a*, **18***b* each of which is shaded in **FIG. 1** to facilitate viewing thereof. Fin-shaped members **16***a*, **16***b*, **18***a*, **18***b* are disposed on a feed structure **19** over a cavity (not visible in **FIG. 1**) in the cavity plate **12** to form the notch antenna element **14***a*. The feed structure **19** will be described below in conjunction with **FIGS. 4 and** 4A. It should be appreciated, however, that a variety of different types of feed structures can be used and several possible feed structures will be described below in conjunction with **FIGS. 2-4A**.

[**0037**] As can be seen in **FIG. 1**, members **16***a*, **16***b* are disposed along a first axis **20** and members **18***a*, **18***b* are disposed along a second axis **21** which is orthogonal to the first axis **20**. Thus the members **16***a*, **16***b* are substantially orthogonal to the members **18***a*, **18***b*.

[**0038**] By disposing the members **16***a*, **16***b* orthogonal to members **18***a*, **18***b* in each unit cell, each unit cell is responsive to orthogonally directed electric field polarizations. That is, by disposing one set of members (e.g. members **16***a*, **16***b*) in one polarization direction and disposing a second set of members (e.g. members **18***a*, **18***b*) in the orthogonal polarization direction, an antenna which is responsive to signals having any polarization is provided.

[**0039**] In this particular example, the unit cells **14** are disposed in a regular pattern which here corresponds to a rectangular grid pattern. Those of ordinary skill in the art will appreciate, of course, that the unit cells **14** need not all be disposed in a regular pattern. In some applications, it may be desirable or necessary to dispose the unit cells **14** in such a way that the orthogonal elements **16***a*, **16***b*, **18***a*, **18***b* of each individual unit cell are not aligned between every unit cell **14**. Thus, although shown as a rectangular lattice of unit cells **14**, it will be appreciated by those of ordinary skill in the art, that the antenna **10** could include but is not limited to a square or triangular lattice of unit cells **14** and that each of the unit cells can be rotated at different angles with respect to the lattice pattern.

[**0040**] In one embodiment, to facilitate the manufacturing process, at least some of the fin-shaped members **16***a* and **16***b* can be manufactured as "back-to-back" fin-shaped members as illustrated by member **22**. Likewise, the fin-shaped members **18***a* and **18***b* can also be manufactured as "back-to-back" the fin shaped members as illustrated by member **23**. Thus, as can be seen in unit cells **14***k* and **14***k*', each half of a back-to-back fin-shaped member forms a portion of two different notch elements.

[**0041**] The plurality of fins **16***a*, **16***b* (generally referred to as fins **16**) form a first grid pattern and the plurality of fins **18***a*, **18***b* (generally referred to as fins **18**) form a second grid pattern. As mentioned above, in the embodiment of **FIG. 1**, the orientation of each of the fins **16** is substantially orthogonal to the orientation of each of the fins **18**.

[**0042**] The fins **16***a*, **16***b* and **18***a*, **18***b* of each radiator element **14** form a tapered slot from which RF signals are launched for each unit cell **14** when fed by a balanced symmetrical feed circuit (described in detail in conjunction with **FIGS. 2-4A** below).

[**0043**] By utilizing symmetric back-to-back fin-shaped members **16**, **18** and a balanced feed, each unit cell **14** is symmetric. The phase center for each polarization is concentric within each unit cell. This allows the antenna **10** to be provided as a symmetric antenna.

[**0044**] This is in contrast to prior art notch antennas in which phase centers for each polarization are slightly displaced.

[**0045**] It should be noted that reference is sometimes made herein to antenna **10** transmitting signals. However, one of ordinary skill in the art will appreciate that antenna **10** is equally well adapted to receive signals. As with a conventional antenna, the phase relationship between the various signals is maintained by the system in which the antenna is used.

[**0046**] In one embodiment, the fins **16**, **18** are provided from an electrically conductive material. In one embodiment, the fins **16**, **18** are provided from solid metal. In some embodiments, the metal can be plated to provide a plurality of plated metal fins. In an alternate embodiment, the fins **16**, **18** are provided from a nonconductive material having a conductive material disposed thereover. Thus, the fin structures **16**, **18** can be provided from either a plastic material or a dielectric material having a metalized layer disposed thereover.

[**0047**] In operation, RF signals are fed to each unit cell **14** by the balanced symmetrical feed **19**. The RF signal radiates from the unit cells **14** and forms a beam, the boresight of which is orthogonal to cavity plate **12** in a direction away from cavity plate **12**. The pair of fins **16**, **18** can be thought of as two halves making up a dipole. Thus, the signals fed to each substrate are ordinarily 180° out of phase. The radiated signals from antenna **10** exhibit a high degree of polarization purity and have greater signal power levels which approach the theoretical limits of antenna gain.

[**0048**] In one embodiment, the notch element taper of each transition section of tapered slot formed by the fins **16***a*, **16***b* is described as a series of points in a two-dimensional plane as shown in tabular form in Table I.

TABLE I

Notch Taper Values

z(inches)	x(inches)
0	.1126
.025	.112
.038	.110
.050	.108
.063	.016

TABLE I-continued

Notch Taper Values	
z(inches)	x(inches)
.075	.103
.088	.1007
.100	.098
.112	.094
.125	.0896
.138	.0845
.150	.079
.163	.071
.175	.063
.188	.056
.200	.0495
.212	.0435
.225	.0375
.238	.030

[**0049**] It should be appreciated, of course that the size and shape of the fin-shaped elements **16**, **18** (or conversely, the size of the slot formed by the fin-shaped elements **16**, **18**) can be selected in accordance with a variety of factors including but not limited to the desired operating frequency range. In general, however, a fin-shaped member which is relatively short with relatively fast opening rate provides a higher degree of cross-polarization isolation at relatively wide scan angles compared with the degree of cross-polarization isolation provided from a fin-shaped member which is relatively long. It should be appreciated, however that if the fin-shaped member is too short, low frequency H-plane performance can be degraded.

[**0050**] Also, a relatively long fin-shaped element (with any opening rate) can result in an antenna characteristic having VSWR ripple and relatively poor cross-polarization performance.

[**0051**] The antenna **10** also includes a matching sheet **30** disposed over the elements **14**. It should be understood that in **FIG. 1** portions of the matching sheet **30** have been removed to reveal the elements **14**. In practice, the matching sheet **30** will be disposed over all elements **14** and integrated with the antenna **10**.

[**0052**] The matching sheet **30** has first and second surfaces **30***a*, **30***b* with surface **30***b* preferably disposed close to but not necessarily touching the fin-shaped elements **16**, **18**. From a structural perspective, it may be preferred to having the matching sheet **30** physically touch the fin-shaped members. Thus, the precise spacing of the second surface **30***b* from the fin-shaped members can be used as a design parameter selected to provide a desired antenna performance characteristic or to provide the antenna having a desired structural characteristic.

[**0053**] The thickness, relative dielectric constant and loss characteristics of the matching sheet can be selected to provide the antenna **10** having desired electrical characteristics. In one embodiment, the matching sheet **30** is provided as a sheet of commercially available PPFT (i.e. Teflon) having a thickness of about 50 mils.

[**0054**] Although the matching sheet **30** is here shown as a single layer structure, in alternate embodiments, it may be desirable to provide the matching sheet **30** as multiple layer structure. It may be desirable to use multiple layers for structural or electrical reasons. For example, a relatively stiff layer can be added for structural support. Or, layers having different relative dielectric constants can be combined to such that the matching sheet **30** is provided having a particular electrical impedance characteristic.

[**0055**] In one application, it may be desirable to utilize multiple layers to provide the matching sheet **30** as an integrated radome/matching structure **30**.

[**0056**] It should thus be appreciated that making fins shorter improves the cross-polarization isolation characteristic of the antenna. It should also be appreciated that using a radome or wide angle matching (WAIM) sheet (e.g. matching sheet **30**) enables the use of even shorter fins which further improves the cross-polarization isolation since the radome/matching sheet makes the fins appear electrically longer.

[**0057**] Referring now to **FIG. 2**, a radiator element **100** which is similar to the radiator element formed by fin-shaped members **16***a*, **16***b* of **FIG. 1**, is one of a plurality of radiators elements **100** forming an antenna array according to the invention. The radiator element **100** which forms one-half of a unit cell, similar to the unit cell **14** (**FIG. 1**), includes a pair of substrates **104***c* and **104***d* (generally referred to as substrates **104**) which are provided by separate fins **102***b* and **102***c* respectively. It should be noted that substrates **104***c*, **104***d* correspond to the fin-shaped members **16***a*, **16***b* (or **18***a*, **18***b*) of **FIG. 1** while fins **102***a*, **102***b* correspond to the back-to-back fin-shaped elements discussed above in conjunction with **FIG. 1**. The fins **102***b* and **102***c* are disposed on the cavity plate **12** (**FIG. 1**). Fin **102***b* also includes substrate **104***b* which forms another radiator element in conjunction with substrate **104***a* of fin **102***a*. Each substrate **104***c* and **104***d* has a planar feed which includes a feed surface **106***c* and **106***d* and a transition section **105***c* and **105***d* (generally referred to as transition sections **105**), respectively. The radiator element **100** further includes a balanced symmetrical feed circuit **108** (also referred to as balanced symmetrical feed **108**) which is electromagnetically coupled to the transition sections **105**.

[**0058**] The balanced symmetrical feed **108** includes a dielectric **110** having a cavity **116** with the dielectric having internal surfaces **118***a* and external surfaces **118***b*. A metalization layer **114***c* is disposed on the internal surface **118***a* and a metalization layer **120***c* is disposed on the external surface **118***b*. In a similar manner, a metalization layer **114***d* is disposed on the internal surface **118***a* and a metalization layer **120***d* is disposed on the external surface **118***b*. It should be appreciated by one of skill in the art that the metalization layer **114***c* (also referred to as feed line or RF feed line **114***c*) and the metalization layer **120***c* (also referred to as ground plane **120***c*) interact as microstrip circuitry **140***a* wherein the ground plane **120***c* provides the ground circuitry and the feed line **114***c* provides the signal circuitry for the microstrip circuitry **140***a*. Furthermore, the metalization layer **114***d* (also referred to as feed line or RF feed line **114***d*) and the metalization layer **120***d* (also referred to as ground plane **120***d*) interact as microstrip circuitry **140***b* wherein the ground plane **120***d* provides the ground circuitry and the feed line **114***d* provides the signal circuitry for the microstrip circuitry **140***b*.

[**0059**] The balanced symmetrical feed **108** further includes a balanced-unbalanced (balun) feed **136** having an

RF signal line **138** and first RF signal output line **132** and a second RF signal output line **134**. The first RF signal output line **132** is coupled to the feed line **114***c* and the second RF signal output line **134** is coupled to the feed line **114***d*. It should be appreciated two 180° baluns **136** are required for the unit cell similar to unit cell **14**, one balun to feed the radiator elements for each polarization. Only one balun **136** is shown for clarity. The baluns **136** are required for proper operation of the radiator element **100** and provide simultaneous dual polarized signals at the output ports with relatively good isolation. The baluns **136** can be provided as part of the balanced symmetrical feed **108** or as separate components, depending on the power handling and mission requirements. A first signal output of the balun **136** is connected to the feed line **114***c* and the second RF signal output of the balun **136** is connected to the feed line **114***d*, and the signals propagate along the microstrip circuitry **140***a* and **140***b*, respectively, and meet at signal null point **154** with a phase relationship 180 degrees out of phase as described further herein after. It should be noted that substrate **104***c* includes a feed surface **106***c* and substrate **104***d* includes a feed surface **106***d* that is diposed along metalization layer **120***c* and **120***d*, respectively.

[**0060**] The radiator element **100** provides a co-located (coincident) radiation pattern phase center for each polarization signal being transmitted or received. The radiator element **100** provides cross polarization isolation levels in the principal plane and in the diagonal planes to allow scanning beams out to 60°.

[**0061**] In operation, RF signals are fed differentially from the balun **136** to the signal output line **132** and the signal output line **134**, here at a phase difference of 180 degrees. The RF signals are coupled to microstrip circuitry **140***a* and **140***b*, respectively and propagate along the microstrip circuitry meeting at signal null point **154** at a phase difference of 180 degrees where the signals are destructively combined to zero at the feed point. The RF signals propagating along the microstrip circuitry **140***a* and **140***b* are coupled to the slot **141** and radiate or "are launched" from transition sections **105***c* and **105***d*. These signals form a beam, the boresight of which is orthogonal to the cavity plate **12** in the direction away from the cavity **116**. The RF signal line **138** is coupled to receive and transmit circuits as is know in the art using a circulator (not shown) or a transmit/receive switch (not shown).

[**0062**] Field lines **142, 144, 146** illustrate the electric field geometry for radiator element **100**. In the region around metalization layer **120***c*, the electric field lines **150** extend from the metalization layer **120***c* to the feed line **114***c*. In the region around metalization layer **120***d* the electric field lines **152** extend from the feed line **114***d* to the metalization layer **120***d*. In the region around feed surface **106***c*, the electric field lines **148** extend from the metalization layer **120***c* to the feed line **114***c*. In the region around feed surface **106***d*, the electric field lines **149** extend from the feed line **114***d* to the metalization layer **120***d*. At a field point **154** (also referred to as a signal null point **154**), the electric field lines **148** and **149** from the feed lines **114***c* and **114***d* substantially cancel each other forming the signal null point **154**. The arrangement of feed lines **114***c* and **114***d* and transition sections **105***c* and **105***d* reduce the excitation of asymmetric modes which increase loss mismatch and cross polarization. Here, the launched TEM modes shown as electric field lines **142** are transformed through intermediate electric field lines **144** having Floquet modes shown as field lines **146**. Received signals initially having Floquet modes collapse into balanced TEM modes.

[**0063**] The pair of substrates **104***c* and **104***d* and corresponding transition sections **105***c* and **105***d* can be thought of as two halves making up a dipole. Thus, the signals on feed lines **114***c* and **114***d* will ordinarily be 180° out of phase. Likewise, the signals on each of the feed lines of the orthogonal transitions (not shown) forming the unit cell similar to the unit cell **14** (**FIG. 1**) will be 180° out of phase. As in a conventional dipole array, the relative phase of the signals at the transition sections **105***c* and **105***d* will determine the polarization of the signals transmitted by the radiator element **100**.

[**0064**] In an alternative embodiment, the metalization layer **120***c* and **120***d* along the feed surface **106***c* and **106***d*, respectively, can be omitted with the metalization layer **120***c* connected to the feed surface **106***c* where they intersect and the metalization layer **120***d* connected to the surface **106***d* where they intersect. In this alternative embodiment, the feed surface **106***c* and **106***d* provide the ground layer for the microstrip circuitry **140***a* and **140***b*, respectively along the bottom of the substrate **104***c* and **104***d*, respectively.

[**0065**] In another alternate embodiment, amplifiers (not shown) are coupled between the balun **136** signal output lines **132** and **134** and the transmission feeds **114***c* and **114***d* respectively. In this alternate embodiment, most of the losses associated with the balun **136** are behind the amplifiers.

[**0066**] Referring now to **FIGS. 3 and 3**A in which like elements in **FIGS. 2, 3** and 3A are provided having like reference designations, a radiator element **100**' (also referred to as an electrically short crossed notch radiator element **100**') includes a pair of substrates **104***c*' and **104***d*' (generally referred to as substrates **104**'). It should be noted that substrates **104***c*', **104***d*' correspond to the fin-shaped members **16***a*, **16***b* (or **18***a*, **18***b*) of **FIG. 1**. Each substrate **104***c*' and **104***d*' has a pyramidal feed which includes a feed surface **106***c*' and **106***d*' and a transition section **105***c*' and **105***d*' (generally referred to as transition sections **105**') respectively. The transition sections **105**' and feed surfaces **106**' differ from the corresponding transition sections **105** and feed surfaces **106** of **FIG. 2** in that the transition sections **105**' and feed surfaces **106**' include notched ends **107** forming an arch. The feed surfaces **106***c*' and **106***d*' are coupled with a similarly shaped balanced symmetrical feed **108**' (also referred to as a raised balanced symmetrical feed).

[**0067**] The transition section **105**' has improved impedance transfer into space. It will be appreciated by those of ordinary skill in the art, the transition sections **105**' can have an arbitrary shape, for example, the arch formed by notched ends **107** can be shaped differently to affect the transfer impedance to provide a better impedance match. The taper of the transition sections **105**' can be adjusted using known methods to match the impedance of the fifty ohm feed to free space.

[**0068**] More specifically, the balanced symmetrical feed **108**' includes a dielectric **110** having a cavity **116** with the dielectric having internal surfaces **118***a* and external surfaces **118***b*. A metalization layer **114***c* is disposed on the internal surface **118***a* and a metalization layer **120***c* is disposed on the external surface **118***b*. In a similar manner, a metalization layer **114***d* is disposed on the internal surface **118***a* and a metalization layer **120***d* is disposed on the external surface **118***b*. It should be appreciated by one of skill in the art that the RF feed line **114***c* and the metalization layer **120***c* (also referred to as ground plane **120***c*) interact as microstrip circuitry **140***a* wherein the ground plane **120***c* provides the ground circuitry and the feed line **114***c* provides the signal circuitry for the microstrip circuitry **140***a*. Furthermore, the or RF feed line **114***d* and the metalization layer **120***c* (also referred to as ground plane **120***d*) interact as microstrip circuitry **140***b* wherein the ground plane **120***d* provides the ground circuitry and the feed line **114***d* provides the signal circuitry for the microstrip circuitry **140***b*.

[**0069**] The balanced symmetrical feed **108**' further includes a balun **136** similar to balun **136** of **FIG. 2**. A first signal output of the balun **136** is connected to the feed line **114***c* and the second RF signal output of the balun **136** is connected to the feed line **114***d* wherein the signals propagate along the microstrip circuitry **140***a* and **140***b*, respectively, and meet at signal null point **154**' with a phase relationship 180 degrees out of phase. Again, it should be noted that substrate **104***c* includes a feed surface **106***c* and substrate **104***d* includes a feed surface **106***d* that is diposed along metalization layer **120***c* and **120***d*, respectively. The radiator element **100**' provides a co-located (coincident) radiation pattern phase center for each polarization signal being transmitted or received. The radiator element **100** provides cross polarization isolation levels in the principal plane and in the diagonal planes to allow scanning beams approaching 60°.

[**0070**] In operation, RF signals are fed differentially from the balun **136** to the signal output line **132** and the signal output **134**, here at a phase difference of 180 degrees. The signals are coupled to microstrip circuitry **140***a* and **140***b*, respectively and propagate along the microstrip circuitry meeting at signal null point **154**' at a phase difference of 180 degrees where the signals are destructively combined to zero at the feed point. The RF signals propagating along the microstrip circuitry **140***a* and **140***b* are coupled to the slot **141** and radiate or "are launched" from transition sections **105***c*' and **105***d*'. These signals form a beam, the boresight of which is orthogonal to the cavity plate **12** in the direction away from cavity **116**. The RF signal line **138** is coupled to receive and transmit circuits as is known in the art using a circulator (not shown) or a transmit/receive switch (not shown).

[**0071**] Field lines **142, 144, 146** illustrate the electric field geometry for radiator element **100**'. In the region around metalization layer **120***c*, the electric field lines **150** extend from the metalization layer **120***c* to the feed line **114***c*. In the region around metalization layer **120***d* the electric field lines **152** extend from the feed line **114***d* to the metalization layer **120***d*. In the region around feed surface **106***c*', the electric field lines **148** extend from the metalization layer **120***c* to the feed line **114***c*. In the region around feed surface **106***d*', the electric field lines **149** extend from the feed line **114***d* to the metalization layer **120***d*. At a signal null point **154**', the RF field lines from the RF feed lines **114***c* and **114***d* substantially cancel each other forming a signal null point **154**'. The arrangement of RF feed lines **114***c* and **114***d* and transition sections **105***c*' and **105***d*' reduce the excitation of asymmetric modes which increase loss mismatch and cross polarization. Here, the launched TEM modes shown as electric field lines **142** are transformed through intermediate electric field lines **144** having Floquet modes shown as field lines **146**. Received signals initially having Floquet modes collapse into balanced TEM modes.

[**0072**] In one embodiment the radiator element **100**' includes fins **102***b*' and **102***c*' (generally referred to as fins **102**') having heights of less than $0.25\lambda_L$, where λ_L refers to the wavelength of the low end of a range of operating wavelengths. Although in theory, radiator elements this short should stop radiating or have degraded performance, it was found the shorter elements actually provided better performance. The fins **102***b*' and **102***c*' are provided with a shape which matches the impedance of the balanced symmetrical feed **108**' circuit to free space. The shape can be determined empirically or by mathematical techniques known in the art. The electrically short crossed notch radiator element **100**' includes portions of two pairs of metal fins **102***b*' and **102***c*' disposed over an open cavity **116** provided by the balanced symmetrical feed **108**'. Each pair of metal fins **102**' is disposed orthogonal to the other pair of metal fins (not shown).

[**0073**] In one embodiment, the cavity **116** wall thickness is 0.030 inches. This wall thickness provides sufficient strength to the array structure and is the same width as the radiator fins **102**' used in the aperture. Radiator fin **102**' length, measured from the feed point in the throat of the crossed fins **102**' to the top of the fin is 0.250 inches without a radome (not shown) and operating at a frequency of 7-21 GHz. The length may possibly be even shorter with a radome/matching structure (e.g. matching sheet **30** in **FIG. 1**). It should be appreciated the impedance characteristics of the radome affect the signal transition into free space and could enable shorter fins **102**'. It will be appreciated by those of ordinary skill in the art that the cavity **116** wall dimensions and the fin **102**' dimensions can be adjusted for different operating frequency ranges.

[**0074**] The theory of operation behind the electrically short crossed notch radiator element **100**' is based on the Marchand Junction Principle. The original Marchand balun was designed as a coax to balanced transmission line converter. The Marchand balun converts the signal from an unbalanced TEM mode on a first end of the coaxial line to a balanced mode on a second end. The conversion takes place at a virtual junction where the fields in one mode (TEM) collapse and go to zero and are reformed on the other side as the balanced mode with very little loss due to the conservation of energy. Mode field cancellation occurs when the RF field on the transmission line is split into two signals, 180 degrees out-of-phase from each other and then combined together at a virtual junction. This is accomplished by splitting the signal at a junction equidistant from two opposing boundary conditions, such as open and short circuits. For the electrically short crossed notch radiator element **100**', the input for one polarization is a pair of microstrip lines provided by feed surfaces **106**' and notched ends **107** (operating in TEM mode) which feed one side with a zero degree signal and the other side with a 180 degrees out-of-phase signal. These signals come together at a virtual junction signal null point **154**', also referred to as the throat of the electrically short crossed notch radiator element **100**'.

[**0075**] At the signal null point **154**', the fields collapse and go to zero and are reformed on the other side in the balanced slotline of the electrically short crossed notch radiator element **100**' and propagate outward to free space. The two opposing boundary conditions for the electrically short crossed notch radiator element **100**' are the shorted cavity beneath the element **100**' and the open circuit formed at the tip (disposed near electric field lines **146**) of each pair of the radiator fins **102***b*' and **102***c*'. The operation of the virtual junction is reciprocal for both transmit and receive.

[**0076**] In one embodiment the short radiating fins and cavity are molded as a single unit to provide close tolerances at the gap where the four crossed fins **102**' meet. The balanced symmetrical feed circuit **108**' can also be molded to fit into the cavity area below the fins **102**' further simplifing the assembly. For receive applications balun circuits **136** are included in the balanced symmetrical feed circuit **108**' further reducing the profile for the array. The short crossed notch radiator element **100**' represents a significant advance over conventional wideband notch radiators by providing broad bandwidth in a relatively smaller profile using printed cirucit board technology and relatively short radiator elements **100**'. The radiator elements **100**' use co-located (coincident) radiation pattern phase centers which are advantageous for certain applications and the physically relatively short profile. Other wideband notch radiators, including the more complex quad notch radiator, do not have the wide angle diagonal plane cross-polarization isolation characteristics of the electrically short crossed notch radiator element **100**'. The combination of the balanced symmetrical feed circuit **108**' and the short fins **102**' provides a reactively coupled notch antenna. The reactively coupled notch enables the use of shorter fin lengths, thereby improving the cross-pol isolation. The length of the fins **102**' directly impacts the wideband performance and the cross-polarization isolation levels acheived.

[**0077**] In another embodiment, the fins **102**' are much (previous discussion page 15 line 6 had less than . . . guess this should be much shorter) shorter than approximately 0.25λL, where λ_L refers to the wavelength of the low end of a range of operating wavelengths and the broadband dual polarized electrically short crossed notch antenna radiator element **100**' transmits and receives signals with selective polarization with co-located (coincident) radiation pattern phase centers having excellent cross-polarization isolation and axial ratio in the principal and diagonal planes. When coupled with the inventive balanced symmetrical feed arrangement, the radiator element **100**' provides a low profile and broad bandwidth. In this embodiment, short fins **102**' also provide a reactively coupled notch antenna. The length of the prior art fins was determined to be the main source of the poor cross-polarization isolation performance in the diagonal planes. It was determined that both the diagonal plane co-polarization and diagonal plane cross-polarization levels varied as a function of the electrical length of the fin. A further advantage of the electrically short crossed notch radiator fins used in an array environment is the high cross polarization isolation levels achieved in the diagonal planes out past ±fifty degrees of scan as compared to current notch radiator designs which can scan out to only ±twenty degrees.

[**0078**] Referring now to **FIG. 4**, a unit cell **202** includes a plurality of fin-shaped elements **204***a*, **204***b* disposed over a balanced symmetrical pyramidal feed circuit **220**. Each pair of radiator elements **204***a* and **204***b* is centered over the balanced symmetrical feed **220** which is disposed in an aperture (not visible in **FIG. 4**) formed in the cavity plate **12** (**FIG. 1**). The first one of the pair of radiator elements **204***a* is substantially orthogonal to the second one of the pair of radiator elements **204***b*. It should be appreciated that no RF connectors are required to couple the signal from to the balanced symmetrical feed circuit **220**. The unit cell **202** is disposed above the balanced symmetrical feed **220** which provides a single open cavity. The inside of the cavity walls are denoted as **228**.

[**0079**] Referring to **FIG. 4A**, the exemplary balanced symmetrical feed **220** of the unit cell **202** includes a housing **226** having a center feed point **234** and feed portions **232***a* and **232***b* corresponding to one polarization of the unit cell and feed portions **236***a* and **236***b* corresponding to the orthogonal polarization of the unit cell. The housing **226** further includes four sidewalls **228**. Each of the feed portions **232***a* and **232***b* and **236***a* and **236***b* have an inner surface and includes a microstrip feed line (also referred to as RF feed line) **240** and **238** which are disposed on the respective inner surfaces. Each microstrip feed line **240** and **238** is further disposed on the inner surfaces of the respective sidewalls **228**. The microstrip feed lines **238** and **240** cross under each corresponding fin-shaped substrate **204***a*, **204***b* and join together at the center feed point **234**. The center feed point **234** of the unit cell is raised above an upper portion of the sidewalls **228** of the housing **226**. The housing **226**, the sidewalls **228** and the cavity plate **212** provide the cavity **242**. The microstrip feed lines **240** and **238** cross at the center feed point **234**, and exit at the bottom along each wall of the cavity **242**. As shown a microstrip feed **244***b*, formed where the metalization layer on sidewall **228** is removed, couples the RF signal to the aperture **222** in the cavity plate **212**. In the unit cell **202**, a junction is formed at the center feed point **234** and according to Kirchoff's node theory the voltage at the center feed point **234** will be zero.

[**0080**] In one particular embodiment, the balanced symmetrical feed **220** is a molded assembly that conforms to the feed surface of the substrate of the fins **204***a* and **204***b*. In this particular embodiment, the microstrip feed lines **240** and **238** are formed by etching the inner surface of the assembly. In this particular embodiment, the housing **226** and the feed portions **232** and **236** molded dielectrics. In this embodiment, the radiator height is 0.250 inches, the balanced symmetrical feed **220** is square shaped with each side measuring 0.285 inches and having a height of 0.15 inches. The corresponding lattice spacing is 0.285 inches for use at a frequency of 7-21 GHz. At the center feed point **234**, a 0.074 inch square patch of ground plane material is removed to allow the RF fields on the microstrip feed lines **240** and **238** to propagate up the radiator elements **204** and radiate out the aperture. In order to radiate properly the microstrip feed lines **240** and **238** for each polarization are fed 180 degrees out-of-phase so when the two opposing signals meet at the center feed point **234** the signals cancel on the microstrip feed lines **240** and **238** but the energy on the microstrip feed lines **240** and **238** is transferred to the radiator elements **204***a* and **204***b* to radiate outward. For receive signals, the opposite occurs where the signal is directed down the radiator elements **204***a* and **204***b* and is imparted onto the microstrip feed lines **240** and **238** and split into two signals 180 degrees out-of-phase. In another embodiment, the balun (not shown) is incorporated into the balanced symmetrical feed **220**.

[**0081**] Referring now to **FIG. 5**, a curve **272** represents the swept gain of a prior art center radiator element at zero degrees boresight angle versus frequency. Curve **270** represents the maximum theoretical gain for a radiator element and curve **274** represents a curve 6 db or more below the gain curve **270**. Resonances present in the prior art radiator result in reduction in antenna gain as indicated in curve **272**.

[**0082**] Referring now to **FIG. 5A**, a curve **282** represents the measured swept gain of the concentrically fed electrically short crossed notch radiator element **100**' of **FIG. 3** at zero degrees boresight angle versus frequency. Curve **280** represents the maximum theoretical gain for a radiator element and curve **284** represents a curve approximately 1-3 db below the gain curve **280**. The curve has a measurement artifact at point **286** and a spike at point **288** due to grating lobes. Comparing curves **272** and **282**, it can be seen that there is a difference of approximately 6 dB (4 times in power) between the gain of the electrically short crossed notch radiator element **100**' compared to the prior art radiator element. Therefore, approximately four times as many prior art radiator elements (or equivalently four times the aperture size of an array of prior art radiators) would be required to provide the performance of one of the electrically short crossed notch radiator element **100**' of **FIG. 3** over a 9:1 bandwidth range. Because of the performance of the electrically short crossed notch radiator element **100**', the element **100**' can operate as an allpass device.

[**0083**] When fed by a balun approaching ideal performance, the electrically short crossed notch radiator element **100**' can be considered as a 4-port device, one polarization is generated with ports one and two being fed at uniform magnitude and a 180° phase relationship. Ports three and four excited similarly will generate the orthogonal polarization. From two through eighteen GHz, the mismatch loss is approximately 0.5 dB or less over the cited frequency range and 60° conical scan volume. The impedance match also remains well controlled over most of the H-plane scan volume.

[**0084**] Referring now to **FIG. 6**, a set of curves **292-310** illustrate the polarization purity of the electrically short crossed notch radiator element **100**' (**FIG. 3**). The curves are generated for a single antenna element of the type shown in the array of **FIG. 1** embedded in the center of an array with all other radiators terminated.

[**0085**] An embedded element pattern is the element pattern in the array environment that includes the mutual coupling effects. The embedded element pattern taken on a mutual coupling array (MCA) was measured. The data shown was taken on the center element of this array near mid band.

[**0086**] Patterns are given for the co-polarized and cross-polarized performance for the various planes (E, H, and diagonal (D)). As can be seen from the curves **292-310**, the antenna is provided having better than 10 dB cross-polarization isolation over a 60° conical scan volume. Curves **292**, **310** illustrate the co-polarized and cross-polarized patterns of the center element in the electrical plane (E), respectively. Curves **249** and **300** illustrate the co-polarized and cross-polarized patterns of the center element in the magnetic plane (H), respectively. Curves **290** and **296** illustrate the co-polarized and cross-polarized patterns of the center element in the diagonal plane, respectively. Curves **292**, **310**, **249**, **300**, **290**, and **296** illustrate that the electrically short crossed notch radiator element **100**' exhibits good cross-polarization isolation performance.

[**0087**] In an alternate embodiment, an assembly of two sub components, the fins **102** and **102**'and the balanced symmetrical feed circuits **108** and **108**' of **FIGS. 1 and 3** respectively, are provided as monolithic components to guarantee accurate alignment of the fins with each other and equal gap spacing at the feed point. By keeping tolerances at a minimum and unit-to-unit uniformity, consistent performance over scan angles and frequency can be achieved.

[**0088**] In a further embodiment, the fin components of the radiator elements **100** and **100**' can be machined, cast, or injection molded to form a single assembly. For example, a metal matrix composite such as AlSiC can provide a very lightweight, high strength element with a low coefficient of thermal expansion and high thermal conductivity.

[**0089**] In another alternate embodiment, radiator elements **100** and **100**' are protected from the surrounding environment by a radome (not shown) disposed over the radiating elements in the array. The radome can be an integral part of the antenna and used as part of the wideband impedance matching process as a single wide angle impedance matching sheet or an A sandwich type radome can be used as is known in the art.

[**0090**] Referring now to **FIGS. 7 and 7**A in which like elements are provided having like reference designations, a unit cell **160**, which may be used in an array antenna such as the one described above in conjunction with **FIG. 1**, includes a feed portion **162** coupled to a radiator portion **164**. This exemplary unit cell **160** is provided from a pair of orthogonally intersecting printed circuit boards **166***a*, **166***b* on which the radiator portion **162** and feed portion **164** are provided.

[**0091**] In this exemplary unit cell **160**, the radiator portion **164** is includes a pair of cross-notched radiators provided from regions **168***a*, **168***b*, **168***c*, **168***d* and orthogonally intersecting slot regions **170***a* (aligned in a plane with regions **168***a*, **168***b*) and **170***b* (aligned in a plane with regions **168***c*, **168***d*). A notch radiator (also referred to as a notch antenna element) may be provided by etching or otherwise removing portions of conductive material disposed over a dielectric substrate to provide a slot having a desired size, shape and length. The size, shape and length are selected to cause signals fed to one end of the slot to radiate from the other end of the slot with desired radiation characteristics. The unit cell **160** is thus provided having orthogonally intersecting slot regions **170***a*, **170***b* (i.e. regions void of conductive material) as well as the regions **168***a*, **168***b*, **168***c*, **168***d* (which represent regions of conductive material e.g. regions in which conductive material was not removed from the dielectric substrate).

[**0092**] Unlike conventional radiators used in dual-polarized notch arrays, the novel cross-notch radiators described in conjunction with **FIGS. 1-7**, are comprised of two elements, which are orthogonal to each other and which share a coincident phase-center. The cross-notch radiators described above in conjunction with **FIGS. 1-7** have a relatively wide operating bandwidth. Thus, one problem with an array antenna fabricated using such a wide-band radiator is that the antenna suffers from performance limitations due to the nature of the feed circuit.

[**0093**] As described above in conjunction with **FIGS. 1-6**, in one embodiment, the cross-notched radiator (e.g. as shown in **FIGS. 4 and 4**A) can be fed in a two-stage process. Two microstrip-input signals, one for each polarization, are sent into a broadband balun, which divides the signals into two signals having equal amplitude and opposite phase. As shown and described in conjunction with **FIGS. 2-4A**, the output from the balun is then provided to a four port microstrip circuit located in a cavity at the bottom of the radiator. This microstrip circuit cavity-type feed structure establishes a slotline like mode between the two sets of fins that will radiate into free space. This mode is designated as the so-called "odd-mode."

[**0094**] Such a microstrip circuit cavity-type feed structure has two performance limitations. The microstrip balun combined with the feed circuit structure has a fractional operating bandwidth in the range of about 3:1. An antenna provided from an array of wide-band cross-notch radiators of the type described above, however, can have a fractional bandwidth in the range of 10:1 to 20:1. Thus, the range of operation of the microstrip circuit cavity-type feed structure described above in conjunction with **FIGS. 2-4A** is considerably smaller than that of the radiator itself.

[**0095**] Additionally, the balun design without a termination structure would allow equal-amplitude, equal phase signals to be fed into the radiator. This mode is referred to as the "even-mode" and is unwanted since the unwanted mode does not radiate into free space.

[**0096**] In the embodiment of **FIG. 7**, the feed portion **162** includes two slotline fee structures which transition into respective ones of orthogonal notch antenna elements. The antenna elements are provided from two dielectric boards **166***a*, **166***b* which intersect and which are orthogonally disposed in the radiating portion **164**. As mentioned above, the dielectric boards **166***a*, **166***b* have conductive portions which have been etched or otherwise removed to provide both the radiating elements and the feed portion **162** including slotline transmission lines **172**, **174**. Slotline transmission line **172** feeds the element provided from regions **168***a*, **168***b* and slot **170***a* and in fact slotline transmission line **172** merges with (or transitions into) the slot **170***a*. Similarly, Slotline transmission line **174** feeds the element provided from regions **168***c*, **168***d* and slot **170***b* and slotline transmission line **174** merges with (or transitions into) the slot **170***b*.

[**0097**] It should be appreciated that the printed circuit boards **166***a*, **166***b* are aligned such that at least a portion of a centerline region of the first slotline circuit having input port **186***a* and at least a portion of a centerline region of the second slotline circuit having input port **186***b* are substantially aligned such that at least a portion of the first and second slotline circuits share a common centerline.

[**0098**] To provide the intersecting boards, an opening is made in the board **166***b* and the board **166***a* is inserted in to the opening. The board **166***b* is bent in two locations **182**, **184** so as to separate the antenna feed input ports **186***a*, **186***b* while still ensuring that at least a portion of a centerline region of the first slotline transmission line **172** and at least a portion of a centerline region of the second slotline transmission line **174** are substantially aligned such that at least a portion of the first and second slotline transmission lines share a common centerline. This provides the antenna feed circuits having coincident phase-centers for each polarization.

[**0099**] The particular bend radius to used at bend points **182**, **184** can be selected in accordance with the needs of any particular application. It is desirable to select a bend radius which does not significantly degrade antenna performance. Some factors to consider in selecting a bend radius include, but are not limited to the operating frequency and the physical space available to accommodate a unit cell. In general, it is desirable to make the bend radius as large as possible given any mechanical constraints. An appropriate bend radius for any particular application can be selected empirically by measuring S-parameters over frequency for a particular bend radius. It should also be appreciated that the bend need not be provided as a curved radius. Rather the bend may be achieved with a series of bend segments with each of the bend segments corresponding to a flat (or straight) piece of the PCB.

[**0100**] In one embodiment for operation in the 3-10 GHz frequency range, printed circuit boards having a thickness of about 10 mils and a relative dielectric constant of about 2.2 were used. The input impedance of the microstrip lines was about 50 ohms at the input port and about 100 ohms at the transition point from the microstrip line to the slotline transmission line portion of the feed. A 20 mil opening was made in one of the PCBs to accept the other PCB. From a mechanical perspective, it is desirable to make the gap as large as possible while from an electrical perspective, it is desirable to make the gap as small as possible. Thus, there is a trade-off between gap size and electrical performance.

[**0101**] Referring now to **FIG. 7A**, and taking feed structure **172** as representative of feed structure **174**, the feed structure **172** includes antenna element input port **186***a* provided from a first end of a microstrip transmission line **190** which is here shown in phantom since it is on a side of the dielectric board which is not directly visible in this view. The second end of the microstrip transmission line **190** terminates in a Y-shape. One arm of the Y-shape microstrip transmission line is coupled to ground via a conductive path **192**.

[**0102**] The second end (i.e. the Y-shaped end) of the microstrip transmission line **190** overlaps a first end **172***a* (or Y-shape end **172***a*) of the slotline **172** which is provided on a side of the dielectric board which is opposite the microstrip transmission line **190**. The second end **172***b* of the slotline transitions into the slotline **170** (**FIG. 7**) of the radiating antenna element. For this reason, as mentioned above, it is relatively difficult to precisely identify the point at which the feed portion of the unit cell ends (e.g. feed portion **162**) and the radiator portion (e.g. radiator portion **160**) begins. In general, however, the radiator portion begins somewhere "above" the bend region **182** (with the word "above" meaning in a direction toward the radiating element).

[**0103**] The above described double-Y balun is a well-known structure and can be redesigned and optimized for different media. This structure uses the Marchand Principle of field cancellation to convert a signal from an unbalance microstrip mode to a balanced slotline mode, which is required to efficiently feed a notch radiator element. Field cancellation occurs when proper boundary conditions are placed within the circuit. In the embodiment of **FIG. 7A**, the path **192** connects one arm of the microstrip Y to ground thereby providing the arm with a short circuit impedance. The other arm of the microstrip Y is provided having an open circuit impedance. Similarly, region **196** of the slot line **172** is provided having a short circuit impedance while arm **198** is provided having an open circuit impedance by virtue of element **200**.

[**0104**] Referring now to **FIGS. 8-8C**, in which like elements are provided having like reference designations throughout the several views, a feed circuit is provided from a printed circuit board **204** having first and second opposing surfaces **204***a*, **204***b*. Surface **204***a* has a microstrip transmission line **206** disposed thereon with a first end **206***a* adapted to provide an antenna input port and a second end **206***b* having a Y-shape. One arm of the Y-shape at the second end of the microstrip transmission line is coupled via a conductive path **208** to a ground plane **205** on the second side **204***b* (**FIG. 8C**) of the board **204**.

[**0105**] Surface **204***b* has a conductive material (e.g. copper) provided thereon to provide the ground plane **205**. Portions of the conductive material have been removed to provide a slotline transmission line **210** having a first Y-shaped end **210***a* and a second end **210***b*. Although not shown in **FIG. 8C**, the second end **210***b* of the slotline transmission line **210** eventually transitions to a notch antenna element in the same way that slot transmission line **172** (**FIG. 7**) transitions to the notch antenna element slot **170***a* (**FIG. 7**).

[**0106**] It should be appreciated that printed circuit board **204**, microstrip transmission line **206**, conductive path **208** and slotline **210** may be similar to the PCBs **166***a*, **166***b*, microstrip transmission line **190**, path **192** slotline **172** described above in conjunction with **FIGS. 7 and** 7A.

[**0107**] All publications and references cited herein are expressly incorporated herein by reference in their entirety.

[**0108**] Having described the preferred embodiments of the invention, it will now become apparent to one of ordinary skill in the art that other embodiments incorporating their concepts may be used. It is felt therefore that these embodiments should not be limited to disclosed embodiments but rather should be limited only by the spirit and scope of the appended claims.

What is claimed is:

1. A feed circuit comprsing:

a first slotline circuit having a first port and a second port, with the first port being adapted to couple to an antenna;

a second slotline circuit having a first port and a second port, with the first port being adapted to couple to an antenna, said second slotline circuit disposed such that the first and second slotline circuits are orthogonal to each other and such that at least a portion of a centerline region of the first slotline circuit and at least a portion of a centerline region of the second slotline circuit are substantially aligned such that at least a portion of the first and second slotline circuits share a common centerline.

2. The circuit of claim 1 wherein a first one of said first and second slotline circuits is provided having an opening therein and the second one of said first and second slotline circuits is disposed in the opening.

3. The circuit of claim 2 wherein a first one of said first and second slotline circuits is provided having at least one bend.

4. The circuit of claim 2 wherein the first one of said first and second slotline circuits is provided having at least one bend.

5. The circuit of claim 4 wherein the first one of the first and second slotline circuits is provided having two bends.

6. The circuit of claim 1 wherein said first slotline circuit comprises:

a first printed circuit board having first and second opposing surfaces;

a microstrip transmission line disposed on a first one of the first and second opposing surfaces of said first printed circuit board, with a first end of said microstrip transmission line corresponding to the second port of said first slotline circuit; and

a slotline transmission line disposed on a second opposite one of the first and second opposing surfaces of said first printed circuit board and coupled to said microstrip transmission line, with a first end of said slotline transmission line corresponding to the first port of said first slotline circuit.

7. The circuit of claim 6 wherein said second first slotline circuit comprises:

a second printed circuit board having first and second opposing surfaces;

a microstrip transmission line disposed on a first one of the first and second opposing surfaces of said first printed circuit board, with a first end of said microstrip transmission line corresponding to the second port of said first slotline circuit; and

a slotline transmission line disposed on a second opposite one of the first and second opposing surfaces of said first printed circuit board and coupled to said microstrip transmission line, with a first end of said slotline transmission line corresponding to the first port of said first slotline circuit.

8. The circuit of claim 7 wherein a first one of said first and second printed circuit boards is provided having an opening therein and the second one of said first and second printed circuit boards is disposed in the opening.

9. The circuit of claim 8 wherein a first one of said first and second printed circuit boards is provided having at least one bend.

10. The circuit of claim 9 wherein the first one of said first and second printed circuit boards is provided having at least one bend.

11. The circuit of claim 10 wherein the first one of the first and second printed circuit boards is provided having two bends.

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